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GENERATION AND DIAGNOSTICS OF SUPER-IONIZED AIR PLASMAS

AFOSR Grant F4962—01-1-0036

Final Technical Report

Submitted to

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Air Force Office of Scientific Research/NI

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by

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Abstract

This grant has permitted the acquisition of instrumentation to produce and study super-ionized air plasmas in the framework of Professor Kruger's current "Air Plasma Ramparts" MURI research program supported by the Department of Defense Research and Engineering and managed by the Air Force Office of Scientific Research, with Dr. Robert J. Barker (703/696-8574) as Technical Monitor (Grant number AF-F49620-97-1-0316). The goal of the Air Plasma Ramparts program is to discover physical mechanisms to significantly reduce the power budget required to create and maintain atmospheric pressure air plasmas with electron number densities greater than 10^{13} cm^{-3} at temperatures below 2000 K. Prior to this grant, our work had demonstrated that stable, diffuse air plasmas with electron number densities approaching 10^{13} cm^{-3} could be produced by means of direct-current (DC) electrical discharges in atmospheric pressure air preheated to 2000 K. However, our work had also shown that the power required to sustain an ionization level of 10^{13} cm^{-3} with a DC discharge is large (25 kW/cm^3). We had then proposed to employ a repetitively pulsed discharge as a way to significantly reduce the power. Using advanced chemical kinetic models, we had predicted that power budget reductions by at least two orders of magnitude could be achieved using a repetitive pulser with pulse duration of the order of 10 ns. The present grant allowed acquisition of the instrumentation necessary to experimentally demonstrate these large power budget reductions. The instrumentation acquired with this grant comprises a repetitive pulse generator (100 kHz, 12 kV, 10 ns), a fast intensified CCD camera for optical diagnostics of the pulsed discharge, a fast sampling oscilloscope for electrical diagnostics of the discharge, and a high current, high voltage DC power supply to study the scalability of discharge plasmas to larger volumes. With the new instrumentation, we have succeeded in generating over $10^{12} \text{ electrons/cm}^3$ in atmospheric pressure air at 2000 K with an average power of 12 W/cm^3 . This power level is much lower, by about a factor of 250, than the power required for producing $10^{12}/\text{cm}^3$ with a DC discharge. **To date, the repetitively-pulsed discharge obtained in our laboratory is the only experimentally-demonstrated technique capable of producing cubic centimeter size atmospheric pressure air plasmas with electron densities in excess of 10^{12} cm^{-3} at power levels of less than about 12 W/cm^3 .**

Introduction

The goal of the parent Air Plasma Ramparts program is to discover physical mechanisms to significantly reduce the power budget required to create and maintain atmospheric pressure air plasmas with electron number densities greater than 10^{13} cm^{-3} at temperatures below 2000 K. Prior to this grant, our work had demonstrated that stable, diffuse discharges with electron number densities approaching 10^{13} cm^{-3} at gas temperatures below 2000 K can be produced in atmospheric pressure air. We had also shown that the power required to sustain an ionization level of 10^{13} cm^{-3} with a DC discharge is about 25 kW/cm^3 . Because these power requirements are too high for many applications, we have sought to reduce the power using a repetitively pulsed approach. This approach seeks to optimize the ionization efficiency and leverage the finite electron recombination lifetime. In the framework of the MURI program, we had developed advanced chemical kinetics models to guide the design of efficient power reduction strategies. We had predicted that power budget reductions by at least two orders of magnitude could be achieved through the use of pulsed electron heating with pulse durations of the order of 10 ns. Guided by these predictions, experiments were conducted in our laboratory in collaboration with Prof. Karl Schoenbach of Old Dominion University. These experiments were made with a single pulse electric discharge. Results confirmed that the ionization efficiency could be increased dramatically, by about two orders of magnitude, through the use of 10 ns pulsed electrical discharges with pulse characteristics tailored to match the ionization and recombination times.

To demonstrate the strategy of electron heating with **repetitive** pulses, we had initially proposed to conduct investigations with a commercially available pulser with a 500-microsecond pulse duration and repetition rates of up to 100 kHz. Shortly before the present grant was attributed, however, we discovered another manufacturer (FID Technology) capable of building a pulser with characteristics much closer to those required to achieve the MURI goals of large power reduction. FID Technology designed, built, and delivered in less than two months a custom made system capable of providing 12 kV, 10 ns pulses at repetition rates of up to 100 kHz. With this system, we have successfully demonstrated the generation and sustainment of an atmospheric pressure air plasma, preheated at 2000 K, with electron number densities in excess of 10^{12} cm^{-3} and a power budget of 12 W/cm^3 . This power level is approximately 250 times lower than the power required with a traditional DC glow discharge.

Additional equipment was acquired to characterize the properties of the repetitive discharge by means of temporally-resolved optical and electrical diagnostics on time scales of one nanosecond or shorter. This equipment includes an intensified CCD camera and a four-channel 1 GHz digitizing oscilloscope. To complement the electrical system, two fast probes were also acquired. The electrical measurements enabled us to determine the plasma conductivity, hence the electron number density, by measuring the current and voltage applied to the plasma during each 10 ns pulse. The intensified CCD camera provided time-resolved images of the pulsed plasma, both during the 10 ns ionization phase and the ensuing recombination phase of a few microseconds. In addition, the intensified CCD camera was coupled with an existing monochro-

mator system to acquire time-resolved emission spectra, during both the ionization and the recombination phases. A digital camera complements the optical system. It has provided high quality photographs of the various DC and pulsed discharges produced in the laboratory. From these pictures, measurements of the plasma diameter were obtained that were used together with electrical measurements to estimate the current density through the discharge. Finally, the grant permitted the acquisition of a 15 kW DC power supply capable of providing voltages of up to 10 kV and current of up to 1.5 A. This DC power supply provides enough current to operate several parallel DC discharges in order to investigate the scalability of air plasma glow discharges to larger volumes.

The equipment acquired under this grant has been extensively used in our investigations of DC and pulsed discharges. Results have already been presented at the 2001 International Conference on Plasma Science and the 2001 International Symposium on Plasma Chemistry. It has enabled us to demonstrate for the first time the feasibility of repetitively pulsed discharges and of power budget reductions by over two orders of magnitude relative to present methods for generating nonequilibrium air plasmas with electron densities in excess of 10^{12} cm^{-3} . This grant has been critical to our studies of the efficient generation of super-ionized air plasmas and to the fundamental understanding of the chemical pathways controlling ionization and recombination.

In the following sections, we describe the major equipment acquired under this grant and we summarize a variety of measurements performed with this equipment. It should be noted that all equipment has performed at or beyond specifications.

1. Repetitive Pulser System

This system comprises a high voltage repetitive pulse generator (HVRPG) and a charging DC power supply. The HVRPG (Model FPG-12-SU-PL) was manufactured by FID Technology (Saint-Petersburg, Russia), and distributed in the United States by the Virginia-based Moose Hill Enterprises (Phone: 540-987-944). Figure 1 shows a photograph of the HVRPG. The charging power supply, model P62B-2508 acquired from Power Ten Inc. (120 Knowles Drive, Los Gatos, CA 95032, Phone: 408-871-1700), is a single phase 208V supply capable of delivering 0- 250 Vdc @ 8 Amps. The repetitive pulser system supplies quasi-square voltage pulses of adjustable amplitude between 4 and 12 kV. Figure 2 shows a typical pulse, with a flat top of 10 ns duration, a 50-90 risetime (time to rise from 50 to 90% of the peak amplitude) of 2 ns, and a 90-50 decay time of 5 ns. The 50 and 90% levels are important because the ionization rate depends exponentially on the electric field. At our operating conditions, a voltage below 50% of the maximum value has negligible effect on gas ionization. The repetition rate is adjustable up to 110 kHz. The pulse-to-pulse jitter is less than 0.25 ns. The output pulse generator voltage has a maximum amplitude of 3 kV on a 25 ohm impedance. The desired 12 kV output amplitude on a 400 Ω impedance load is obtained by means of a cable transformer formed by four 100-ohm coaxial cables acting as transmission lines. The strengths of the FID pulse generator are the use of solid state technology and of an inductive opening switch design. This technology makes for a very com-

pact (30×30×16 cm), reliable, and safe generator (capacitive closing-circuit designs use large, hazardous capacitors). Unlike other commercially available pulse generators (spark-gap, thyatron, or other solid state generators), the FID device offers a unique combination of high operating voltage (up to 5 kV per unit and higher with stacked units) and currents (up to 10 kA), small jitter (less than 1 ns), narrow pulse width (1-10 ns) with sharp risetime, and high pulse repetition frequency. The FID device uses a unique Fast Ionization Device (FID) of the Drift Step Recovery Diode type. In our experiments, the pulser is connected to the plasma in parallel with a 400 Ω resistive load, also provided by FID Technology. The system was installed on-site by an FID Tech engineer who demonstrated operation to specifications and provided us hands on training for troubleshooting and repairing possible damage to the pulser. This training proved useful as we were able to successfully repair the pulser after accidental arcing destroyed two transistors. The total cost of this repetitively pulsed system is approximately \$47,000. Figure 3 shows a photograph of the plasma obtained with this system. As can be seen, the plasma is diffuse in character. Electrical and optical measurements obtained with the equipment described in the following sections confirmed the diffuse nature of the plasma and enabled quantitative measurements of the temperature and electron number density in the plasma.

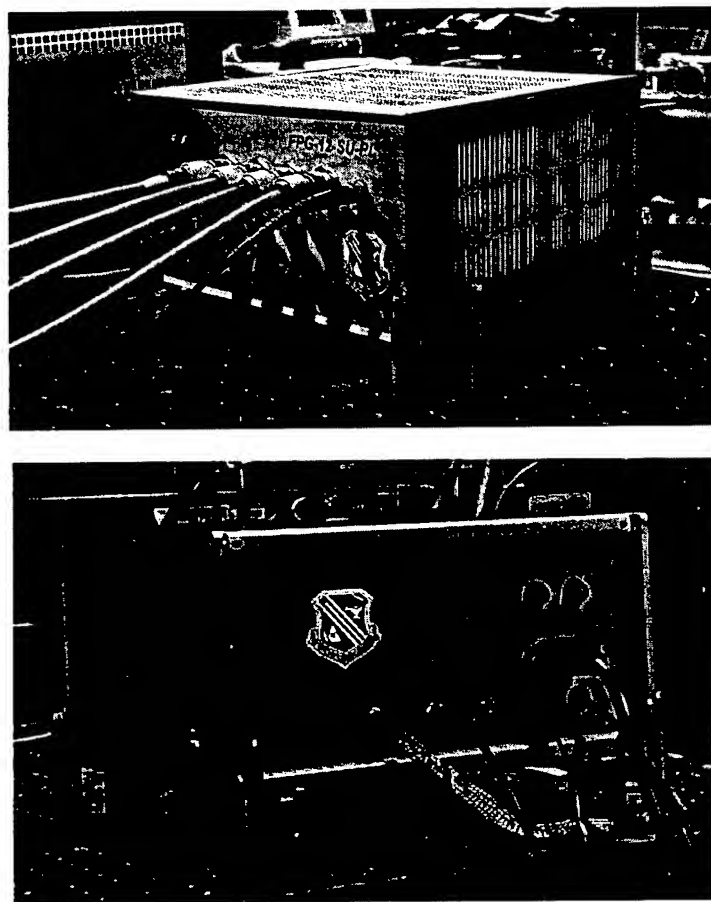


Figure 1. Repetitive pulse generator manufactured by FID Technology (front and back). 4-12 kV, 10 ns square pulses. Pulse repetition frequency: 0 to 110 kHz. Note the four-cable transformer connected to the front of the pulser.

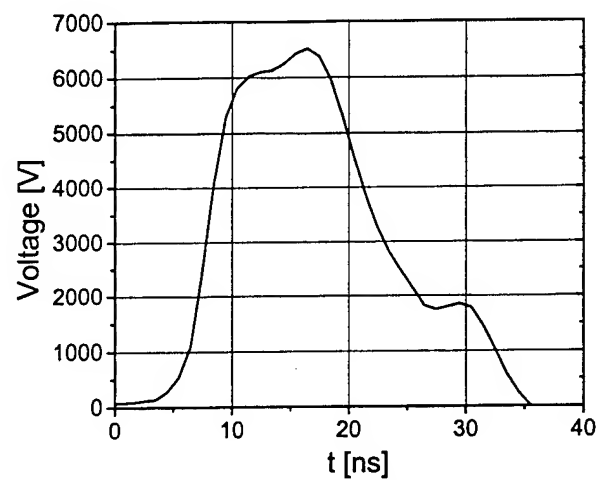


Figure 2. Typical pulse shape.

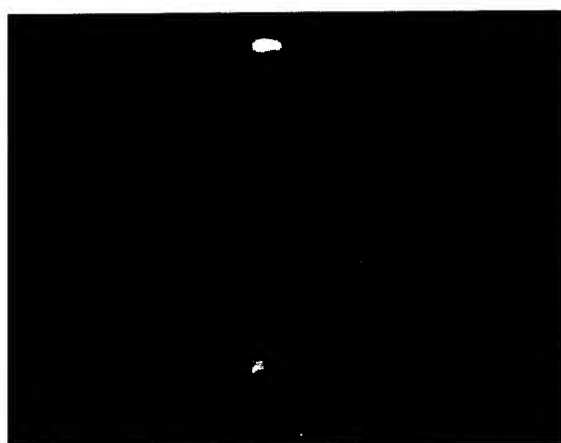


Figure 3. Photograph of repetitive pulse discharge in air at 2000 K, 1 atm.

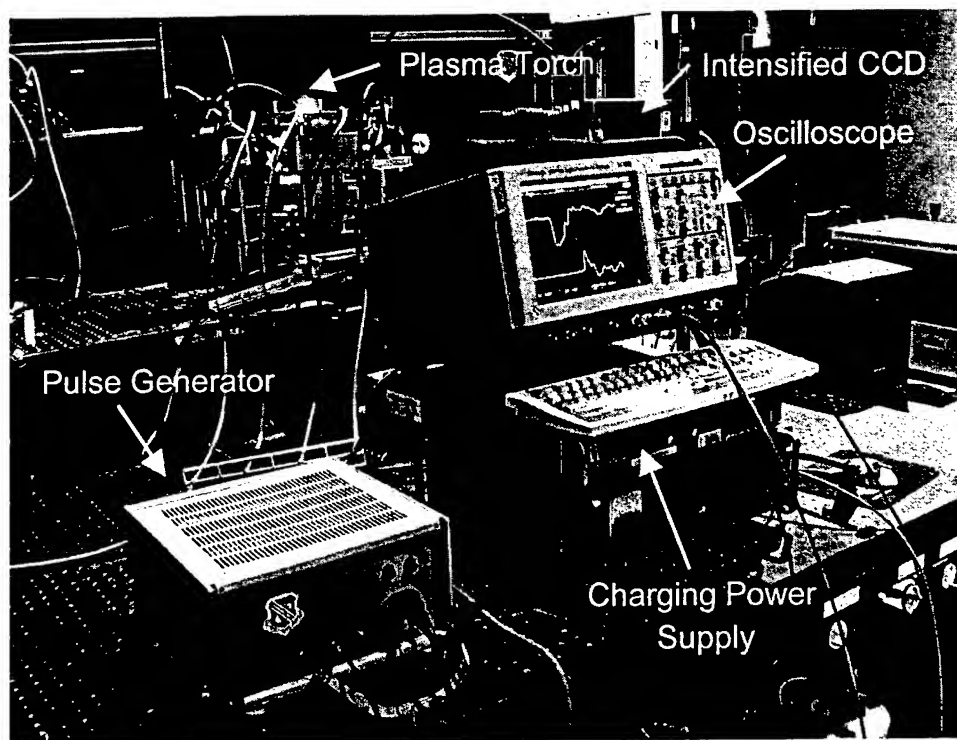


Figure 4. Setup for repetitively pulsed plasma experiments.



Figure 5. Repetitively pulsed discharge applied in atmospheric pressure air preheated to 2000 K. The yellow plume corresponds to thermally heated air at 2000 K. The discharge electrode is applied between two platinum pins affixed on water-cooled stainless-steel electrodes. The discharge current is monitored with a Rogowski coil placed around the top electrode. The voltage across the discharge gap is measured with two fast Lecroy probes. Interelectrode spacing: 1.2 cm.

2. Electrical Diagnostics System

A four-channel digitizing oscilloscope, Tektronix Model TDS7104, was acquired from Tektronix (MS 50-295, PO Box 4600, Beaverton, OR 97076 – Phone: 650-570-5773). This oscilloscope has a 1 GHz/10 Gs sampling rate that provides the required resolution to measure current and voltage signals during even the short (10 ns) ionization phase. The four channels were critical to allow the simultaneous acquisition of current and voltage applied to the discharge, and of pulse control parameters. The cost of this oscilloscope was about \$22,000 (including a \$3525 educational discount). The system was complemented with two ultrafast high voltage probes, Lecroy Model PPE6KV, of 400 MHz frequency response, and 6 kV maximum amplitude. (Vendor: Lecroy, 700 Chestnut Ridge Rd., NY 10977, Phone 914-578-6020). The cost of the two probes was about \$1300.

Figure 4 shows a general overview of the experimental setup, and Figure 5 a close-up of the repetitively pulsed plasma discharge. Figure 5 shows a photograph of the front oscilloscope panel. The screen displays actual traces of the voltage and current through the discharge during operation of the repetitive pulser in air. The third trace corresponds to the signal used to trigger the pulses.

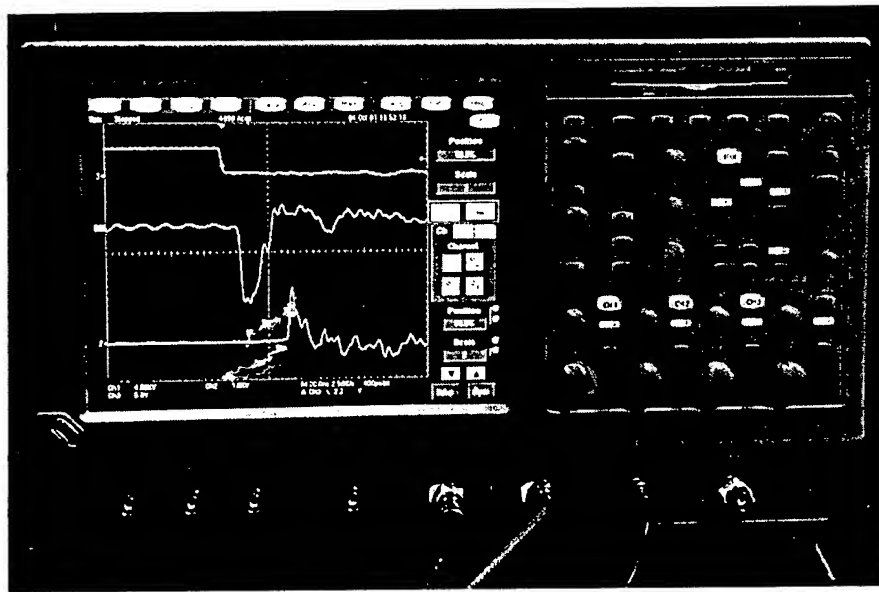


Figure 6. Tektronix TDS 7104 DPO Oscilloscope.

Measurements were made of the pulsed plasma conductivity in order to determine the temporal variations of the electron number density. Figure 7 shows the measured electron density over three plasma pulses. The time-averaged electron density is about 10^{12} cm^{-3} . The power consumption was measured from the current and voltage during the 10 ns pulse. For these measurements, the very high sampling rate of the Tektronix scope is critical. Figures 8 and 9 show the pulse current, measured with a Rogowski coil, and the peak pulse voltage as a function of inter-electrode distance. For an applied voltage of 6 kV across a 1 cm gap, the electric field in the

positive column is about 4520 V/cm (taking into account the measured cathode fall of 1525 V). The peak pulse current is about 250 mA. The discharge diameter is measured to be approximately 3.3 mm. The instantaneous power during one 10-ns pulse is therefore 12 kW/cm³. The pulser duty cycle is approximately 1000, because the pulse repetition frequency is 100 kHz. Thus, the average power consumption to produce 10¹² electrons/cm³ is approximately 12 W/cm³. This value is in good agreement with our theoretical prediction of 9 W/cm³.

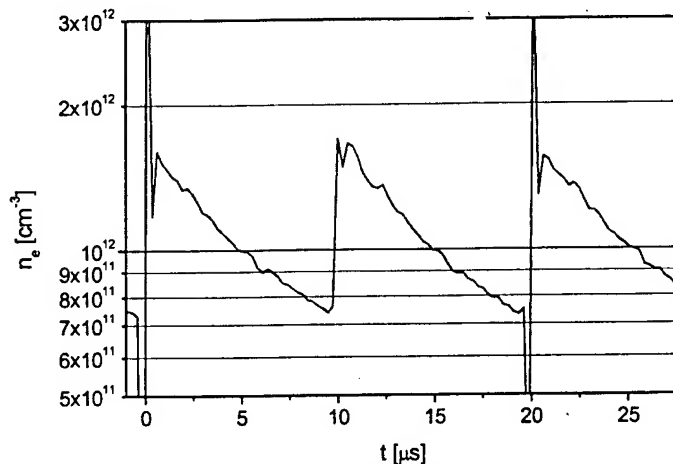


Figure 7. Electron number density measurement in repetitively pulsed discharge in air at 1 atm and 2000 K.

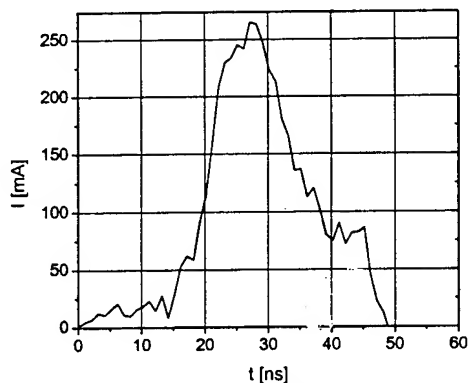


Figure 8. Current pulse measured with Rogowski coil. Peak pulsed current: 240 mA. Peak pulsed voltage: 4520 V for a 1cm gap. Diameter of discharge: 3.3 mm

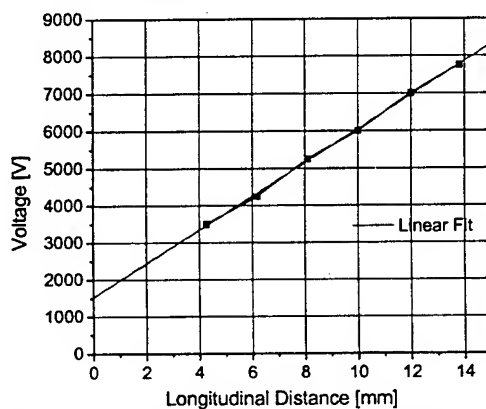


Figure 9. Peak pulse voltage vs gap length. Cathode fall = 1525 V Electric field = 4520 V/cm

3. Optical Diagnostics System

A digital intensified CCD camera system was acquired from Roper Scientific (3660 Quackerbridge Rd., Trenton NJ 08619, Phone: 609-587-9797). The system includes a Model PI-MAX 1024 RB intensified CCD camera with an 18 mm intensifier, and programmable timing generator (Model PTG). The total cost of the system is about \$43,400 (including a \$2,225 educational discount). A new CCD-3000 controller with built-in thermoelectric cooling was also acquired to upgrade our existing SPEX 750M monochromator camera control system (Vendor: Instruments SA, 3880 Park Ave., Edison, NJ 08820, 732-494-8660). The cost of the CCD-3000 controller was about \$8,500 (including a \$405 discount and a \$1000 credit for return of our old CCD2000 controller).

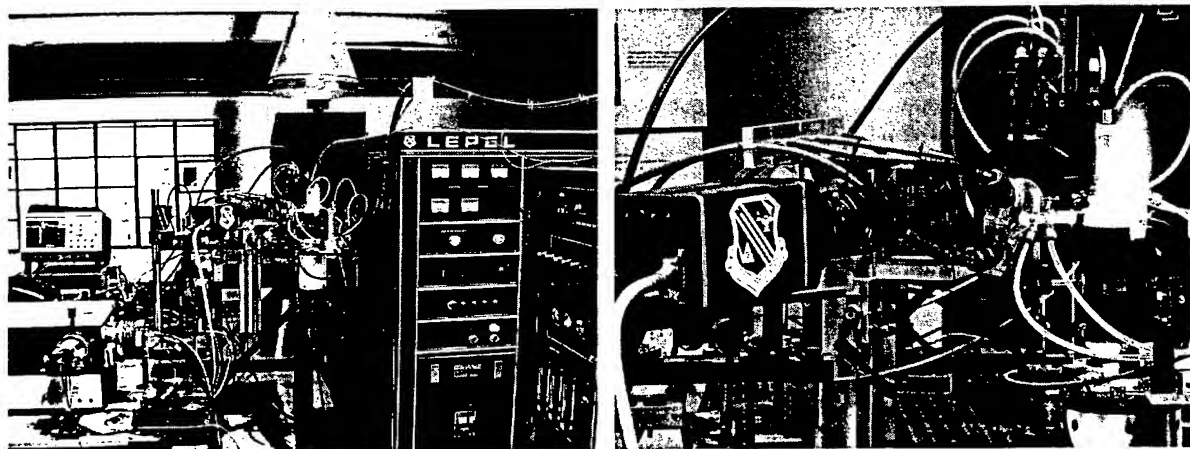


Figure 10. Left: Experimental setup showing the plasma torch facility, the intensified CCD camera, oscilloscope, and spectrometer with non-intensified CCD camera. Right: Close-up view of the intensified CCD camera.

The intensified CCD camera was used to acquire time-resolved images of the pulsed plasma, both during the 10 ns ionization phase and the ensuing recombination phase of a few microseconds. The images shown in Figure 11 were obtained at time intervals of 2 ns with a gating time of 1.5 ns. These images clearly show that the pulsed plasma develops from both electrodes. After approximately 10 ns, the gap appears filled with a uniform and diffuse plasma. Light from the plasma subsequently decays in spatially uniform manner right after the end the pulse.

The intensified CCD camera was also coupled with an existing monochromator system to acquire time-resolved emission spectra, during both the ionization and the recombination phases. Preliminary results (see Figure 12) show that the pulse excites the C state of N_2 and the A state of NO. After the pulse, emission from the C state of N_2 decays to a constant value within 30 ns, and emission from the A state of NO shows a two-step decay, with first an abrupt decrease by over four orders of magnitude from the end of the pulse until 320 ns after the pulse, and then a slower decrease by one order of magnitude until the next pulse. Interpretation of these experimental results is currently in progress.

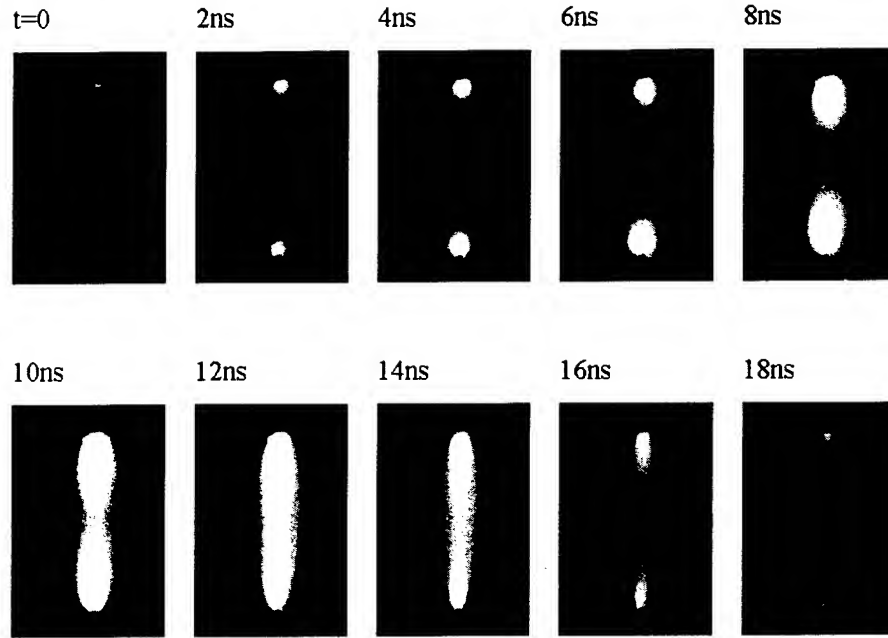


Figure 11. Temporal development of air plasma during a 10 ns pulse. Repetition rate: 100 kHz. 1.5 ns frames.

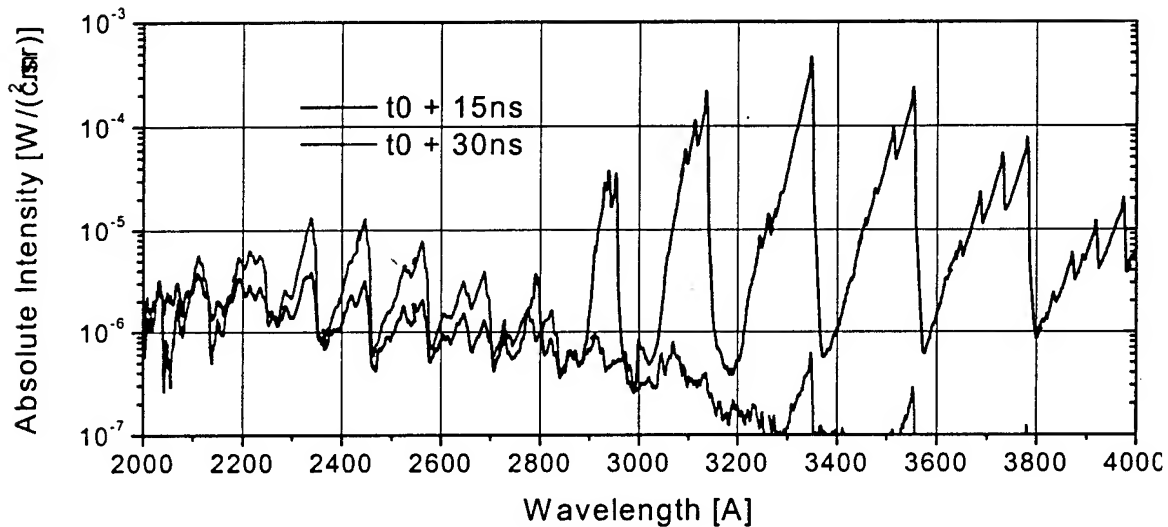


Figure 12. Absolute intensity, time-resolved emission spectra of the repetitively pulsed discharge. t_0 is the time at which the 10 ns electric pulse starts.

Repetitively pulsed discharges thus represent a novel method to produce atmospheric pressure air plasma with low power expenditures and electron number densities in excess of 10^{12} cm^{-3} . Additionally, these discharges produce no noticeable electrode erosion, and can be easily operated in parallel for scalability to large volumes. Figure 13 shows operation of a multi-pin repetitively pulsed discharge with six sets of electrodes in parallel.



Figure 13. Multi-pin repetitively pulsed discharge in preheated (2000 K), atmospheric pressure air. Discharge volume $\sim 1 \text{ cm}^3$. Electron number density: $\sim 10^{12} \text{ cm}^{-3}$.

4. 15 kW DC Power Supply

A high voltage 15 kW DC power supply (model RHVSHP10-15000R) with reversible polarity and voltage and current outputs in the ranges 0-10 kV and 0-1.5 A, respectively, was acquired from Del High Voltage (Address: One Commerce Park, Valhalla, NY 10595, phone: 914-686-3600) for an approximate cost of \$21,000. The front panel of the supply is shown on Figure 14. This power supply has been used for studies of plasma scalability. One method to produce larger plasma volumes is to operate several discharges in parallel. With the dual discharge circuit design sketched in Figure 15, two DC glow discharges have been successfully operated in parallel (see Figure 16). Studies of the spatial properties of the dual discharge are currently in progress. Extensions of the measurement of air plasma discharge characteristics to currents up to 1.5 A are also planned.

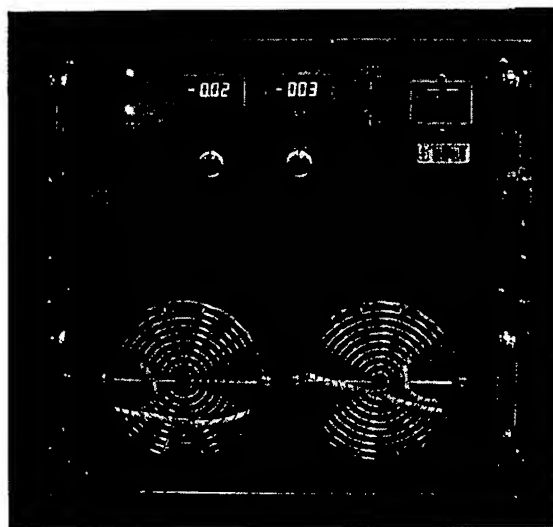


Figure 14. Front panel of the 15 kW Del High Voltage DC power supply.

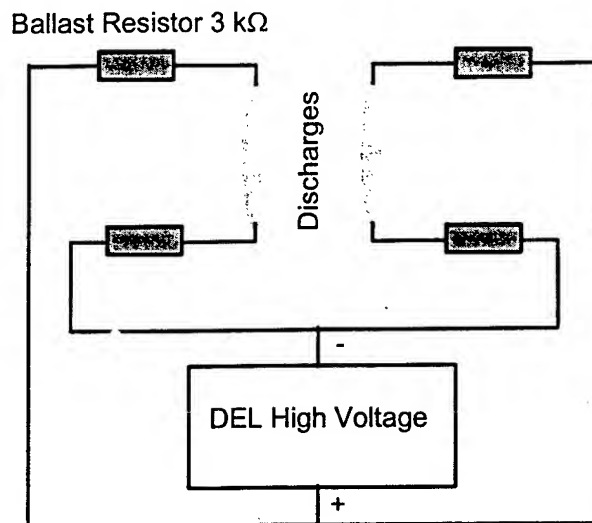


Figure 15. Electrical circuit used for dual-discharges experiments



Figure 16. Dual-discharge in air at atmospheric pressure and room temperature. Electrode gap: 1 cm. Interelectrode separation: 0.95 cm. The gas velocity, current and voltage are equal to 2 m/s, 100 mA and 1.4 kV, respectively.

Summary of Equipment Purchased

High Voltage Repetitive Pulse Generator System with on-site installation (one engineer for one week), 10 ns pulsewidth, 6-12 kV amplitude, 1kHz-100 kHz pulse repetition frequency. Model FPG-12-SU-PL. Vendor: Moose Hill Enterprises, Phone: 540-987-944\$44,878.88

Charging DC power supply for pulser, 0 to 250 Vdc @ 8 Amps, 190-253 VAC Single phase Model P62B-2508. Vendor: Power Ten Inc., 120 Knowles Drive, Los Gatos, CA 95032, Phone: 408-871-1700 1,883.85

High voltage DC power supply with reversible polarity, 15 kW, 0-10 kV, 0-1.5 A, Model RHVSHP10-15000R. Vendor: Del High Voltage (contact: Mr. Steve Soltis), One Commerce Park, Valhalla, NY 10595, phone: 914-686-3600.....\$20,851.63

Digital Intensified CCD Camera System, Model PI-MAX 1024 RB (minus \$2,000 educational discount).....\$38,726.97
Programmable Timing Generator, Model PTG (minus \$225 educational discount).....\$4,627.78
Vendor: Roper Scientific, 3660 Quackerbridge Rd., Trenton NJ 08619, Phone: 609-587-9797

CCD-3000 camera controller with built-in TE-PS. Vendor: Instruments SA, 3880 Park Ave., Edison, NJ 08820, 732-494-8660. (minus \$1,000 credit for return of old CCD2000 controller and preferred customer discount of \$405)\$8,462.42

Digitizing Oscilloscope, 1 GHz, 10 Gs, 4 channels. Tektronix Model TDS7104. Vendor: Tektronix, Address: MS 50-295, PO Box 4600, Beaverton, OR 97076. Phone: 650-570-5773. (minus \$3,525 educational discount).....\$21,706.32

Digital Camera Nikon CoolPix990\$1,626.14

Two High Voltage Probes, Lecroy Model PPE6KV, 400 MHz, 6 kV 314189. Vendor: Lecroy, Address: 700 Chestnut Ridge Rd., NY 10977, Phone 914-578-6020\$1,315.30

Spare transistors for repetitive pulser\$1,000

Publications

Kruger, C.H., Laux, C.O., Yu, L., Packan, D.M., Pierrot, L., "Nonequilibrium Discharges in Air and Nitrogen Plasmas at Atmospheric Pressure," invited plenary lecture at the 15th International Symposium on Plasma Chemistry, Orléans, France, July 9-13, 2001.

Packan, D., Yu, L., Laux, C.O., Kruger, C.H., "Repetitively-Pulsed DC Glow Discharge in Atmospheric Pressure Air: Modeling and Experiments with a 12 kV, 10 ns, 100 kHz Pulse Generator," Proceedings of the 28th IEEE International Conference on Plasma Science, p. 259, Las Vegas, NV, June 17-22, 2001.

Kruger, C.H., Laux, C.O., Packan, D.M., Yu, L., Yalin, A.P., Zare, R.N., Nagulapally, M., Candler, G.V., Kelley, J.D., "Nonequilibrium Discharges in Atmospheric Pressure Air," Proceedings of the 28th IEEE International Conference on Plasma Science, p. 348, Las Vegas, NV, June 17-22, 2001.